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Title: Recent Results from the Microscopic Schrodinger Optical Model

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RECENT RESULTS FROM THE MICROSCOPIC SCHRODINGER OPTICAL MODEL

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Abstract

Recent developments in nucleon-nucleus scattering at intermediate energies led to a model which is entirely predictive and could produce good to excellent agreement with scattering data. Such a model is required by a number of applications: nuclear astrophysics, structure of exotic nuclei, (e,e'N) studies, applied physics, to name a few. In some cases, the necessity stems from lack of relevant data, in others a need to understand the mechanism in order to study other facets of experiment. The model of nucleon-nucleus scattering developed by the Melbourne Group (recently published as a review article in Advances in Nuclear Physics) is discussed as well as results obtained pertaining to the structure of exotic nuclei, and also to neutron-nucleus scattering and the structure of heavy nuclei.

1 Introduction

Nucleon scattering has been one of the primary tools by which the properties of nuclei may be studied. It probes the matter density of nuclei, the distribution of both protons and neutrons, and is thus complementary to electron scattering, which probes the charge and current densities of nuclei. An understanding of the interaction of nucleons with nuclei is crucial for the understanding of not only scattering but all nucleon-induced reactions. Such information is also obtained primarily from scattering.

Traditionally, nucleon scattering from nuclei has been described in terms of an optical potential, by which the many body problem is reduced to one of the scattering of the projectile from the potential encompassing the many body aspects of the problem. That optical potential is usually described phenomenologically by a Woods-Saxon (WS) potential (see, for example, [1]), whose form is influenced by the Fermi-Dirac distribution of nucleons within the nucleus. Success has been achieved in the descriptions of the properties of nuclei as a result of analyses of experiment using such a model.

However, that success must be achieved partly by fitting parameters in the potential to the data being described. In a sense this is numerical inversion, and the description of data by such a phenomenological potential is limited to range encompassed by the data sets which are fitted to determine the parameters. Alongside the development of the phenomenology has been the development of the microscopic models of the optical potential. Those models have as their base the nucleon-nucleon (NN) interaction which is folded with the density of the target to obtain the optical potential. Their purpose is to obtain a prescription for the optical potential that does not depend on any parameter fitting of the data. All results from such a model are thus predictive and is important in obtaining information on nucleon-induced reactions for which there are no data; there are many such instances in nuclear astrophysics and applied physics, for example. Such microscopic models have recently been summarized in a review [2].

The purpose of this paper is to summarize the most recent microscopic model, that developed by the Melbourne group [2], and give a few examples in which its predictive power is necessary. Such a necessity comes from the field of radioactive beam physics, in which the only way to assess the structures of exotic nuclei microscopically is with scattering from hydrogen, which in the inverse kinematics corresponds to proton scattering. The examples discussed herein are the halo nuclei ^{6}He and ^{11}Be. There is also considerable effort in determining the neutron density of heavy nuclei, and the Jefferson Laboratory is undertaking to measure the neutron radius of ^{208}Pb from parity-violating electron scattering. We present analyses of proton and neutron scattering data from ^{208}Pb to determine that neutron radius.

2 Microscopic optical potential

The microscopic optical potential is derived from the g matrices of the nucleon-nucleon (NN) potential; those g matrices are solutions of the Brueckner-Bethe-Goldstone equation in infinite nuclear matter. The Bonn-B NN potential [4] was chosen as the starting point for the calculations presented herein. A local density approximation is used to map the infinite matter solution to the nucleus in question by which an effective NN interaction is defined in medium. When folded with an appropriate ground state density of the target, the microscopic optical potential is obtained naturally incorporating Pauli blocking and density dependences. The potential contains both direct and exchange parts, with the exchange terms arising from the antisymmetrization of the projectile and bound state nucleon wave functions, and so the potential is fully nonlocal. There are no parameters in the model which must be adjusted after the fact to achieve a reasonable fit; all results are obtained from a single calculation and are predictive. Success has been achieved predicting the observables from proton-nucleus scattering for a number of nuclei across a range of energies [2]. For the present cases, the ground state density for ^{208}Pb was obtained from a Skyrme-Hartree-Fock calculation by Brown [5], while the calculations of the light nuclei come from complete $(0+2+4)\hbar\omega$ and $(0+2)\hbar\omega$ shell models for ^{6}He, and ^{10}C and ^{11}Be, respectively. As the g matrix is defined for all two-body spin and isospin channels, the isospin of the projectile selects the correct components of the matrix to define the appropriate optical potential for that projectile. As such the one g matrix defines the optical potentials for both proton and neutron scattering in a natural way. The Coulomb interaction is, of course, also included in the calculations of proton scattering.

The complete details of the calculation of the microscopic optical potential can be found in a recent review article [2], including details of the program DWBA98 [3], with which we calculate the optical potential and all observables.

3 Results

In all cases presented herein, the results of the calculations are predictions. There has been no fitting of the data to which the results have been compared.

3.1 Scattering from ^{208}Pb

We have analyzed 65 proton and neutron elastic scattering data from ^{208}Pb, using the Skyrme-Hartree-Fock (SHF) wave functions of Brown [5]. Two versions of the SHF wave functions are used, corresponding to skin thicknesses (the difference between the neutron and proton radii) of 0.15 (SHF1) and 0.25 fm (SHF2). The SHF1 model is designated the standard model as defined by Brown [5], and is determined from consideration of the Freedman-Pandharipande neutron equation of state. The value of 0.25 fm is based on the mean field calculations of Ring *et al.* [6], which also suggest a value of 0.15 fm, the choice depending on the mean field model used. The proton rms radius is 5.45 fm [5]. Note that we compare proton and neutron scattering analyses given that due to the dominance of the isovector $^1S_0$ channel in the NN interaction, proton scattering primarily probes the neutron density and visa-versa.

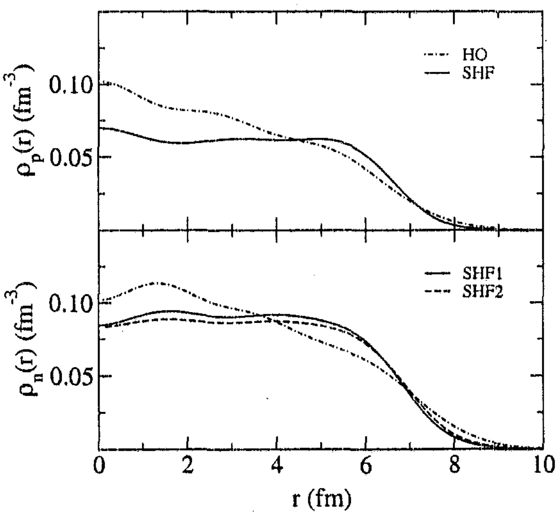

Fig. 1 Proton and neutron densities for ^{208}Pb as obtained from the SHF1 and SHF2 models, as well as an oscillator model as described in the text.

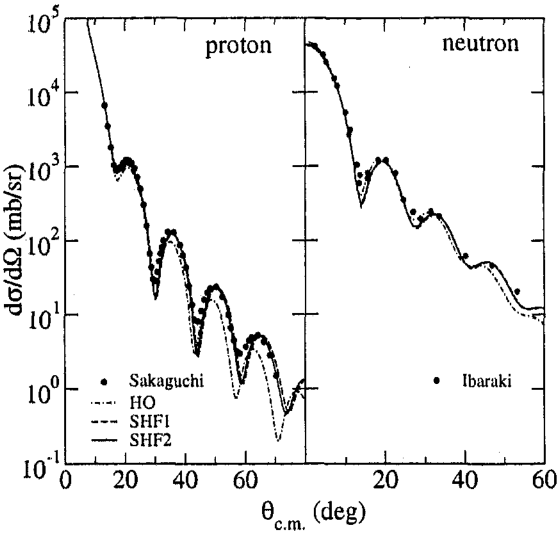

Fig. 2 Differential cross sections for the scattering of 65 MeV protons and neutrons from ^{208}Pb. The proton scattering data of Sakaguchi *et al.* [7] and neutron scattering data of Ibaraki *et al.* [8] are compared to results of the oscillator and Skyrme-Hartree-Fock calculations as described in the text.

The matter density of ^{208}Pb as obtained from these models, as well as a harmonic oscillator (HO) model which reproduces the radii of the SHF1 model, are displayed in Fig. 1. For 65 MeV nucleon scattering, the surface of the nucleus is probed, and so differences in the region near the surface will affect the results of the calculations of the differential cross sections.

The results of the calculations of the differential cross section for the scattering of 65 MeV protons and neutrons from ^{208}Pb are displayed in Fig. 2, wherein comparison is made with the proton scattering data of Sakaguchi *et al.* [7] and neutron scattering data of Ibaraki *et al.* [8]. In the case of neutron scattering, all models well reproduce the data, which is expected given that near the surface the proton densities from all models are in agreement. That is not the case with the results of the proton scattering, in which both SHF models are in much better agreement with the data than the HO model. Near the surface both SHF models give higher neutron densities than the HO model. The data are also slightly better reproduced by the SHF2 model, suggesting that the skin thickness of ^{208}Pb is 0.25 fm.

3.2 Exotic light nuclei

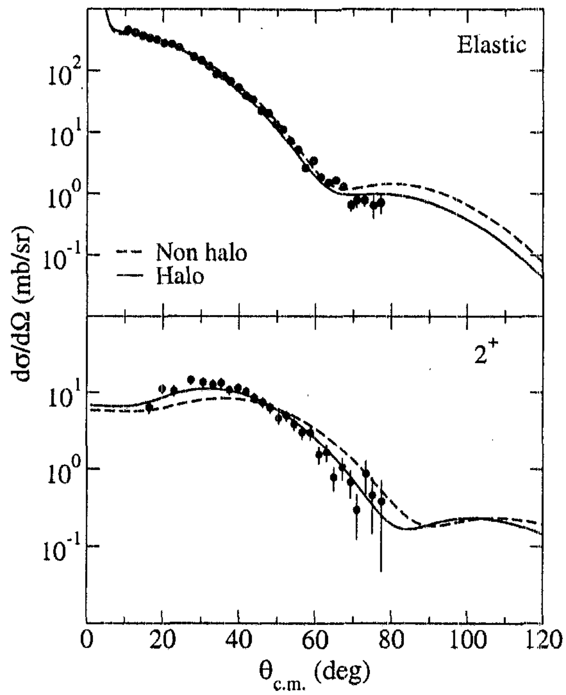

Fig. 3 Differential cross sections for the elastic and inelastic scattering, to the 2^+ (1.8 MeV) state, of $41A$ ^{6}He nuclei from hydrogen. The data from Saclay are compared to the results as discussed in the text.

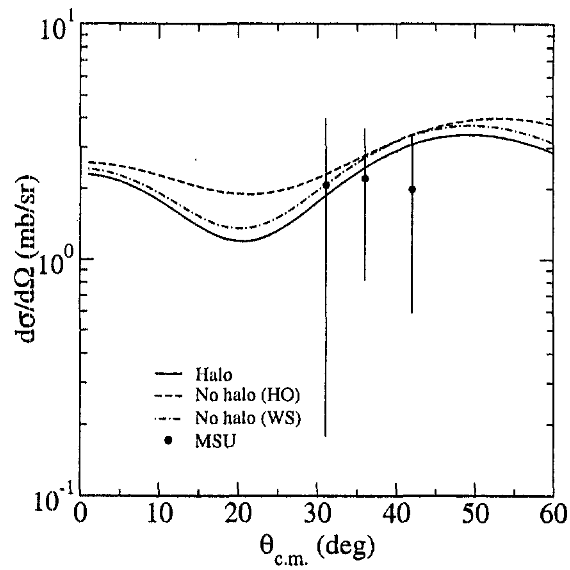

Fig. 4 Differential cross section for the ^{11}Be$(p,n)^{11}$B (IAS) reaction at $30A$ MeV. The data are from MSU.

Some of the nuclei near the drip lines have much larger rms radii than a simple model of structure would suggest. This is due to the very loose binding of the valence nucleons, and studying these structures, known as halos, are very important to advance our knowledge of nuclei, and also in applications, principally in nucleosynthesis, which cannot proceed without them. Much effort has gone into the study of ^{6}He, which has a two-neutron halo, but which has not been firmly established [9]. Fig. 3 displays the differential cross sections for the elastic and inelastic scattering, to the 2^+ (1.8 MeV state) of $41A$ MeV ^{6}He ions from hydrogen. "Halo" signifies a description of ^{6}He in which the neutron density extends much further in radius, as compared to naive shell models, consistent with the loose binding of the two halo neutrons, while "nonhalo" is the result using the naive (packed) shell model. A complete $(0+2+4)\hbar\omega$ shell model calculation gave the ^{6}He wave functions for the calculation of those densities. The elastic scattering data from Saclay supports the halo description of ^{6}He, although there are not enough data beyond 70° to discriminate fully between the halo and nonhalo. The inelastic scattering is of the 2^+ state. Such an excitation from the 0^+ ground state is surfaced peaked, and so this should highlight the role of the halo. The data and analysis confirm uniquely the halo description for ^{6}He.

^{11}Be is another halo nucleus that has been extensively studied, as it is one of the few examples of single neutron halos. The preliminary data from Michigan State University [10] of the differential cross section for the ^{11}Be(p,n) reaction, using $30A$ MeV ^{11}Be ions, to the isobaric analogue state in ^{11}B are displayed in Fig. 4, together with the results of the calculations made using a complete $(0+2)\hbar\omega$ shell model description for the nuclei, again assuming both halo and nonhalo densities for the ^{11}Be nucleus. While it is clear that the statistics of the experiment need to be improved in order to select between the models used, it is encouraging to note that the magnitudes agree so well without any adjustment of any of the structure or interaction details. This "in principle" experiment and analysis gives encouragement for the use of charge exchange reactions to probe exotic nuclei, as has been proposed for the new Coupled Cyclotron facility at Michigan State University.

4 Conclusions

A fully predictive model of nucleon-nucleus scattering has been presented and applied to scattering from ^{208}Pb as well as the halo nuclei ^{6}He and ^{11}Be. In all cases, excellent agreement has been achieved with the data without the need for fitting parameters.

In the case of ^{208}Pb, we have been able to determine that its skin thickness is ~ 0.25 fm, predicting the possible outcome of the proposed electron scattering experiment at the Jefferson Laboratory. This has important implications for the study of heavy nuclei, in which knowledge of the neutron distribution, and its extension beyond that of the proton, is important.

Our model also allows us to investigate the microscopic structures of exotic nuclei, and we have presented two cases: those of ^{6}He and ^{11}Be. By comparison to the recent data collected at Saclay, we have firmly established that ^{6}He is a halo. In the case of ^{11}Be, we have been able to predict the ^{11}Be(p, n) data which gives encouragement to pursue charge exchange reactions as a means to study microscopically the structure of exotic nuclei.

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